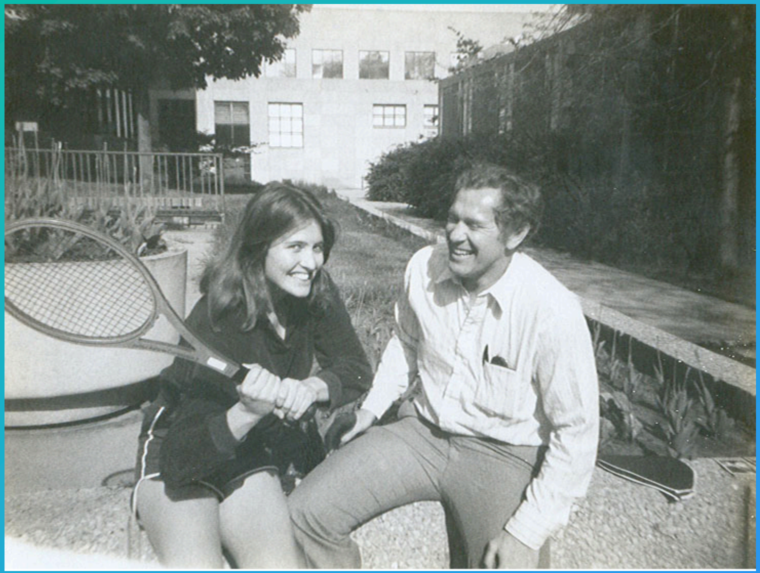
Dark Stars:
Dark Matter annihilation can power the first stars

Katherine Freese
University of Michigan
And
Stockholm University

I followed Keith around at first



- Schramm student
- Remember Moriond

- Bill Press postdoc
- at Harvard CFA
- I should have followed Keith to CERN!

DSU 2016 in Bergen

Beware the fjords


DAVID GRANT presents
A JOHN CARPENTER film
From
ALAN DEAN FOSTER
FIRST
2001: A SPACE ODYSSEY
THEN
THE POSEIDON ADVENTURE
NOW
DARK STAR
A
DS-1
bombed out in space
with a spaced out bomb!
An OPPIDAN ENTERTAINMENTS Release of a JACK H. HARRIS Production Starring DAN O'BANNON and BRIAN NARELLE Produced & directed by JOHN CARPENTER

Collaborators

Doug Spolyar

Paolo Gondolo

Pearl Sandick

Tanja Rindler-Daller

Peter Bodenheimer

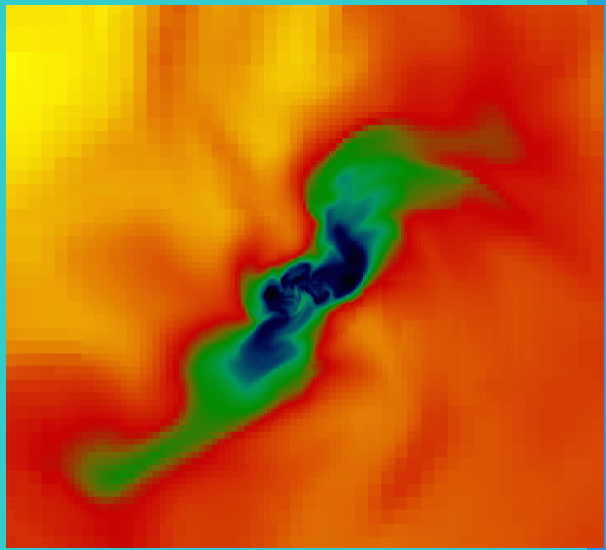
Dark Stars

The first stars to form in the history of the universe may be powered by Dark Matter annihilation rather than by Fusion (even though the dark matter constitutes less than 1% of the mass of the star).

- This new phase of stellar evolution may last millions to billions of years
- Dark Stars can grow to be very large: up to ten million times the mass of the Sun. Supermassive DS are very bright, up to a billion times as bright as the Sun. These can be seen in James Webb Space Telescope, sequel to Hubble Space Telescope.
- Once the Dark Matter runs out, the DS has a fusion phase before collapsing to a big black hole: is this the origin of supermassive black holes?

First Stars: Standard Picture

- Formation Basics:
  - First luminous objects ever.
  - At z = 10-50
  - Form inside DM haloes of $\sim 10^6\ M_\odot$
  - Baryons initially only 15%
  - Formation is a gentle process



Made only of hydrogen and helium from the Big Bang. No other elements existed yet

Dominant cooling Mechanism is

H_2

Not a very good coolant

(Hollenbach and McKee '79)

Hierarchical Structure Formation

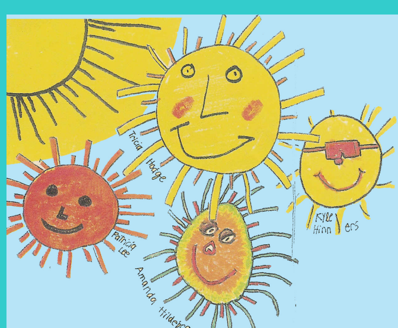
Smallest objects form first (sub earth mass)

Merge to ever larger structures

Pop III stars (inside $10^6\,M_\odot$ haloes) first light

Merge $\rightarrow$ galaxies

Merge $\rightarrow$ clusters



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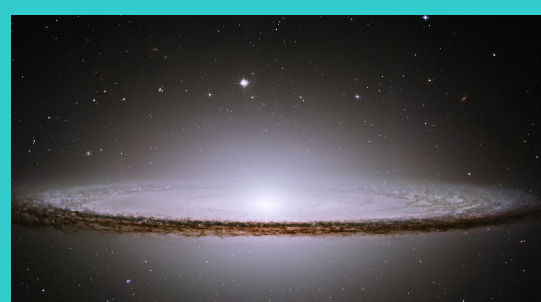


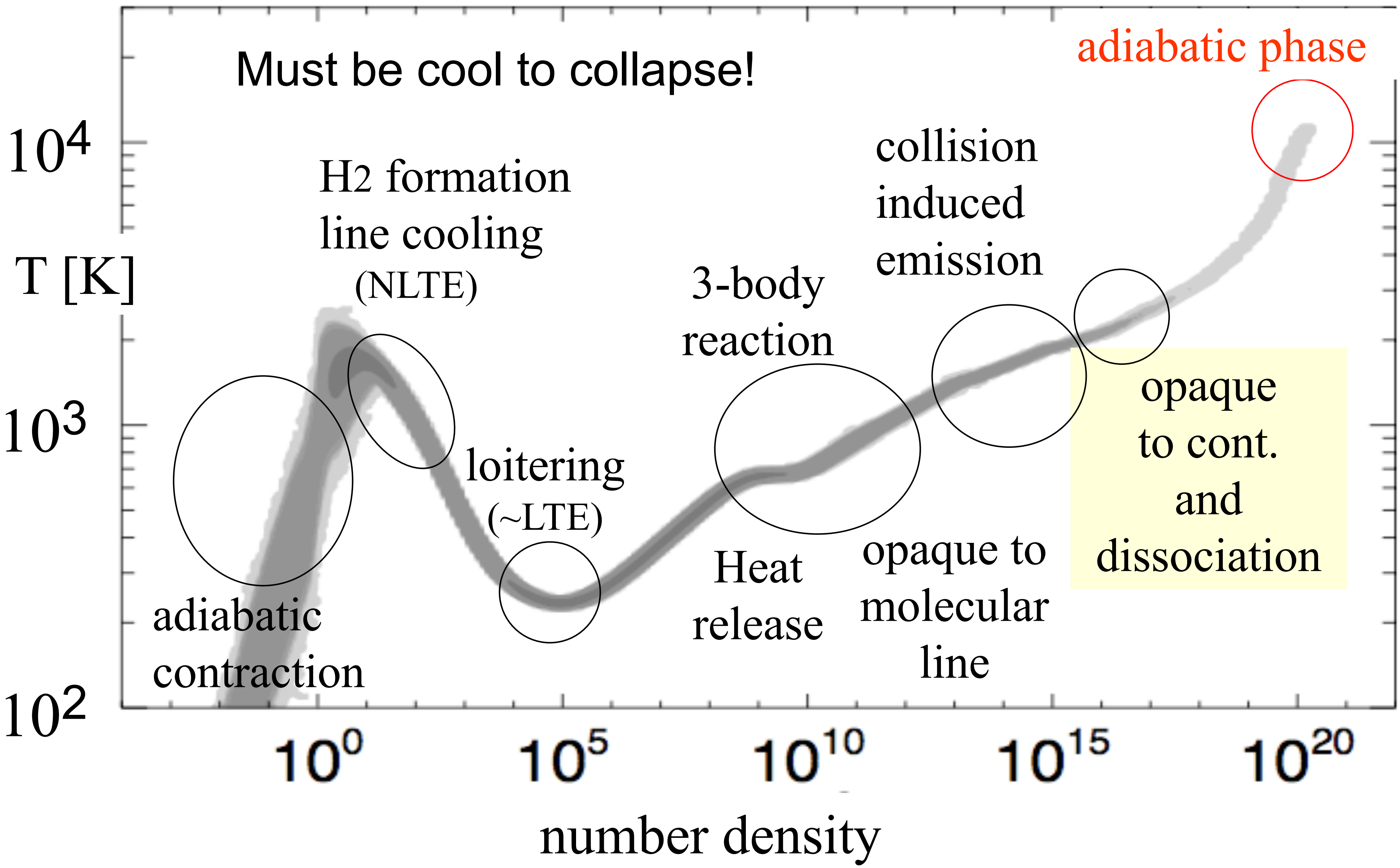
$\rightarrow$

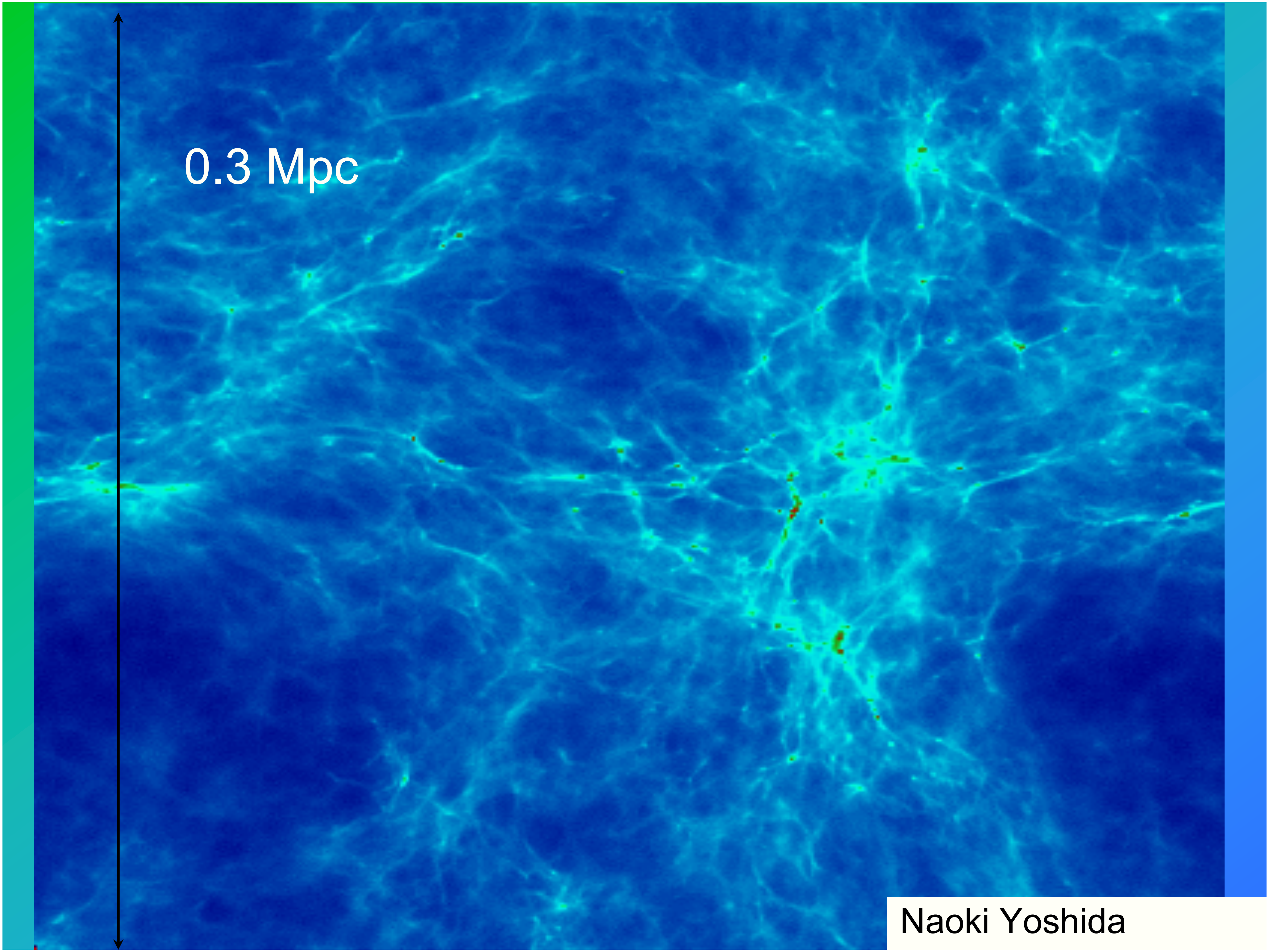
Scale of the Halo

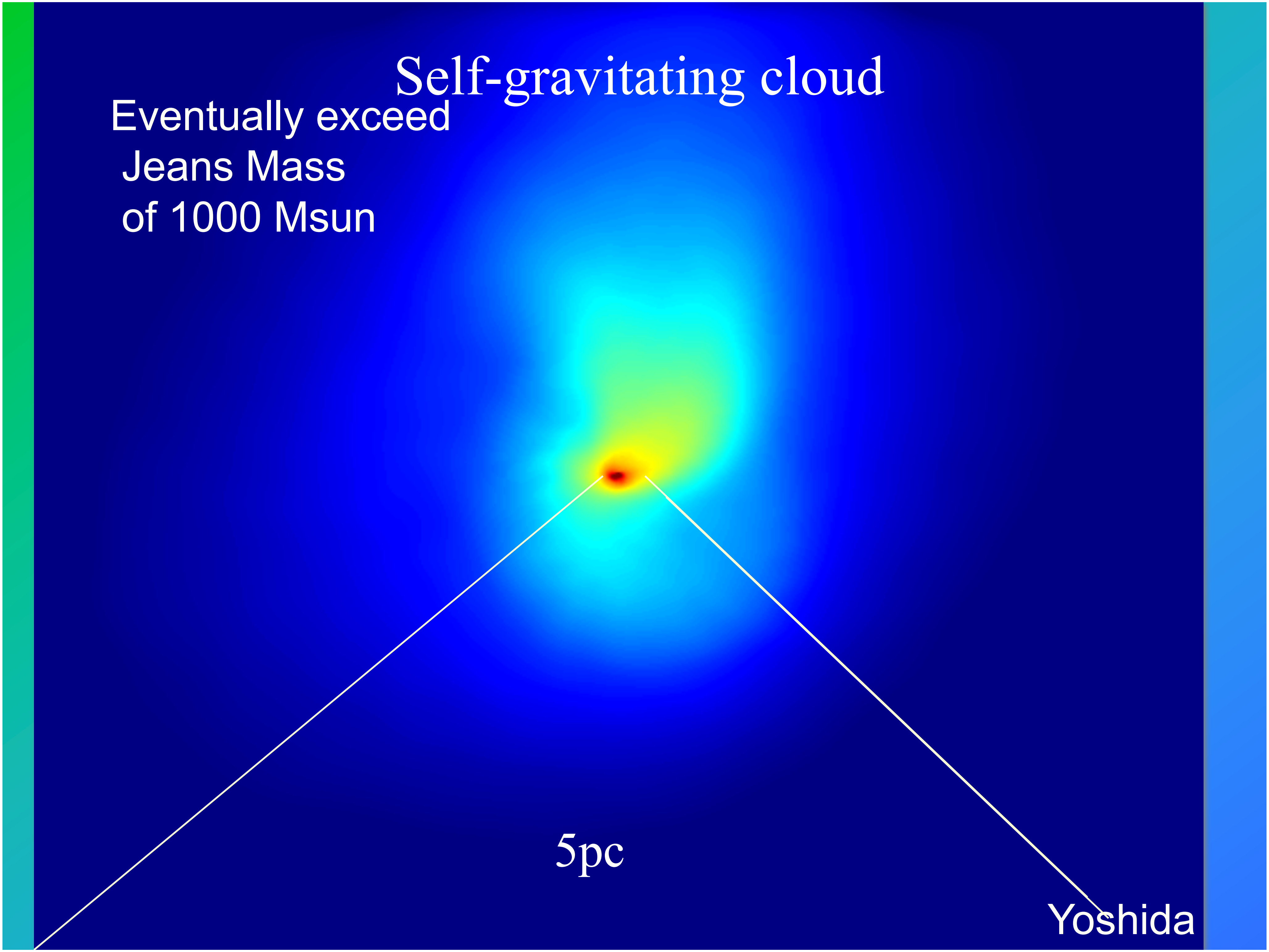
- Cooling time is less than Hubble time.
- First useful coolant in the early universe is H_2 .
- H_2 cools efficiently at around 1000K
- The virial temperature of $10^6\ M_\odot$

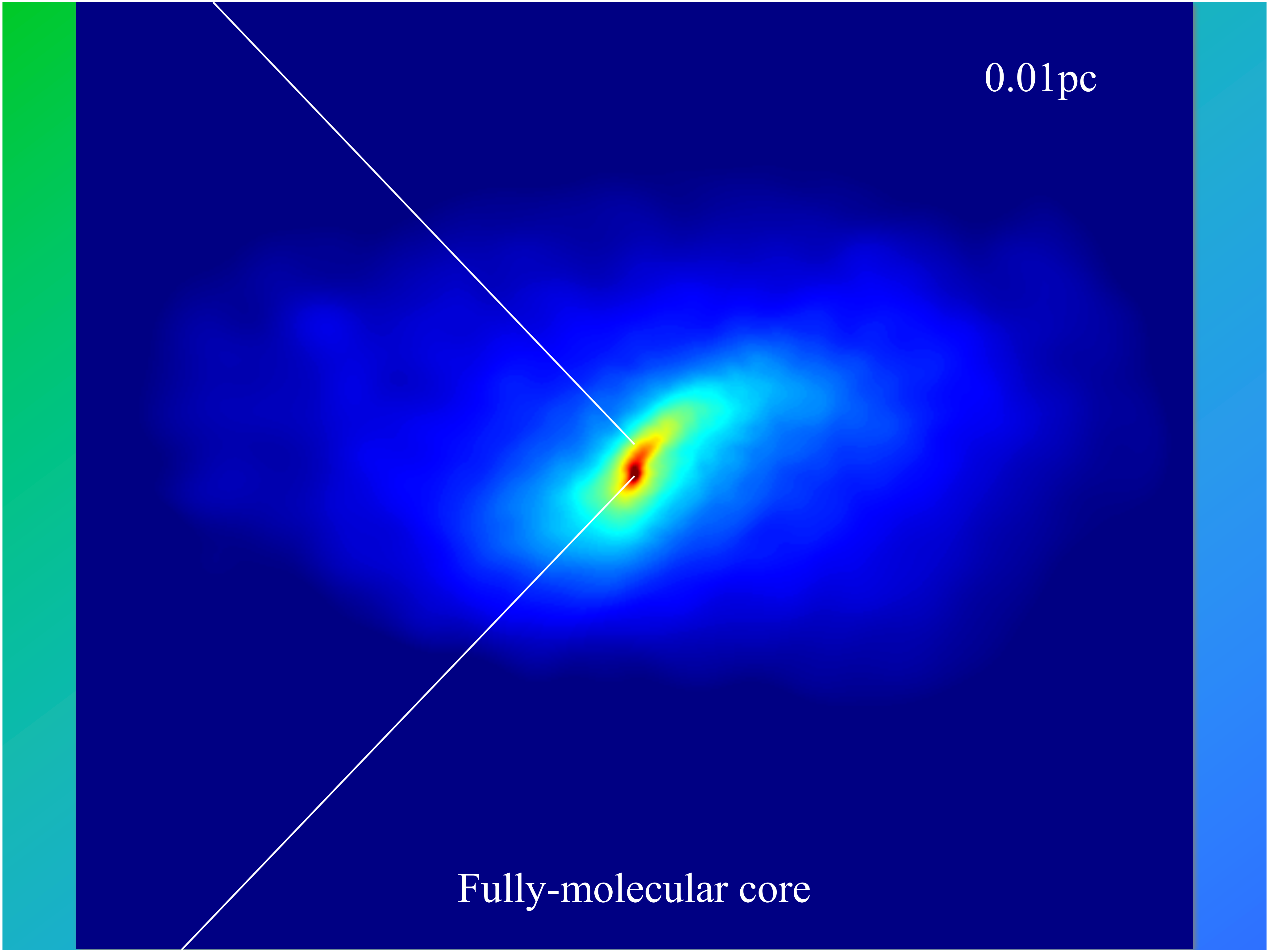
  ~1000K

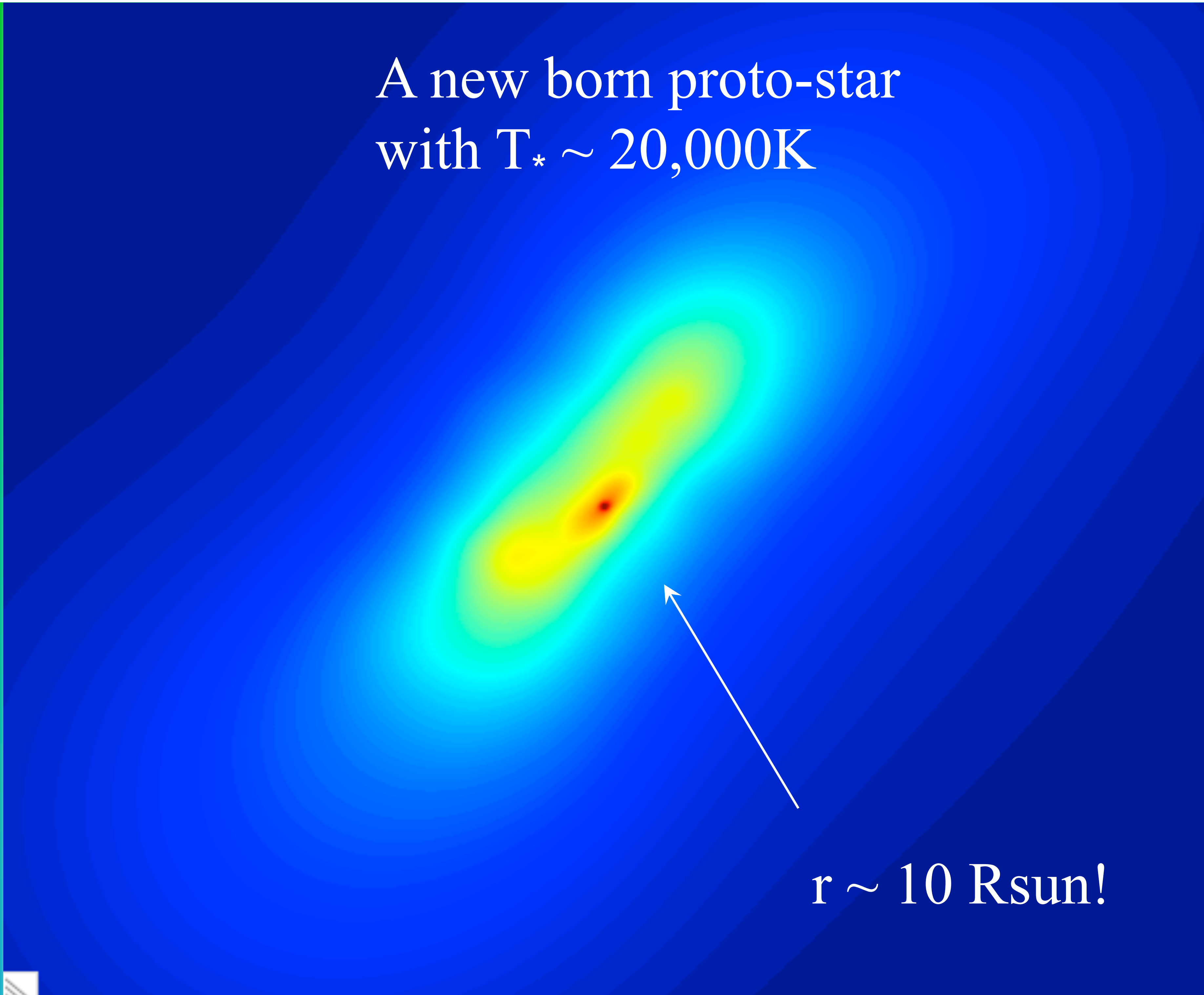
Thermal evolution of a primordial gas




0.3 Mpc
Naoki Yoshida


Self-gravitating cloud
Eventually exceed
Jeans Mass
of 1000 Msun
5pc
Yoshida


0.01pc
Fully-molecular core


A new born proto-star
with T* ~ 20,000K
r ~ 10 Rsun!

Scales

- Halo Baryonic Mass ~ $10^5\ M_\odot$

(Halo Mass $10^6\ M_\odot$)

↓

- Jeans Mass ~ $10^3\ M_\odot$

↓

- Initial Core Mass ~ $10^{-3}\ M_\odot$

↓ Accretion

Final stellar Mass??

feedback effects
McKee and Tan 2008

With DM heating
Much more massive

$100 M_\odot$ Standard Picture

$10^3 - 10^7\ M_\odot$ Dark Star

WIMPs

Mass 1Gev-10TeV (canonical 100GeV)

Annihilation cross section (WIMPS):

$$<\sigma v>_{ann} = 3\times 10^{-26} cm^3/\sec$$

Same annihilation that leads to correct WIMP abundance in today's universe

Same annihilation that gives potentially observable signal in FERMI, PAMELA, AMS

Why DM annihilation in the first stars is more potent than in today's stars: higher DM density

- **THE RIGHT PLACE**:

  one single star forms at the center of a million solar mass DM halo

- **THE RIGHT TIME:**

  the first stars form at high redshift,

  z = 10-50, and density scales as (1+z)^3

Basic Picture

- The first stars form in a DM rich environment
- As the gas cools and collapses to form the first stars, the cloud pulls DM in.
- DM particles are their own antipartners, and annihilate more and more rapidly as the density increases
- DM annihilates to e+/e- and photon endproducts of 100 GeV (or so) which collide with hydrogen, are trapped inside the cloud, and heat it up.
- At a high enough DM density, the DM heating overwhelms any cooling mechanisms; the cloud can no longer continue to cool and collapse. A Dark Star is born, powered by DM.

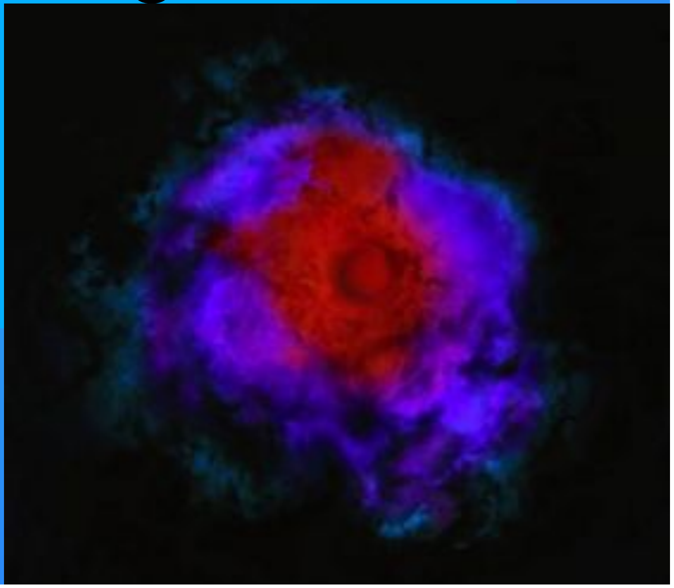
Dark Matter Power vs. Fusion

- DM annihilation is (roughly) 100% efficient in the sense that all of the particle mass is converted to heat energy for the star
- Fusion, on the other hand, is only 1% efficient (only a fraction of the nuclear mass is released as energy)
- Fusion only takes place at the center of the star where the temperature is high enough; vs. DM annihilation takes place throughout the star.

Three Conditions for Dark Stars
(Spolyar, Freese, Gondolo 2007 aka Paper 1)

- I) Sufficiently High Dark Matter Density ?
- 2) Annihilation Products get stuck in star ?
- 3) DM Heating beats H2 Cooling ?

New Phase



Dark Matter Heating

Heating rate:

$$Q_{ann} = n_\chi^2 <\sigma v> \times m_\chi \quad = \frac{\rho_\chi^2 <\sigma v>}{m_\chi}$$

Fraction of annihilation energy deposited in the gas:

$$\Gamma_{DMHeating} = f_Q \, Q_{ann}$$

Previous work noted that at $n \le 10^4 cm^{-3}$ annihilation products simply escape (Ripamonti,Mapelli,Ferrara 07)

f_Q :

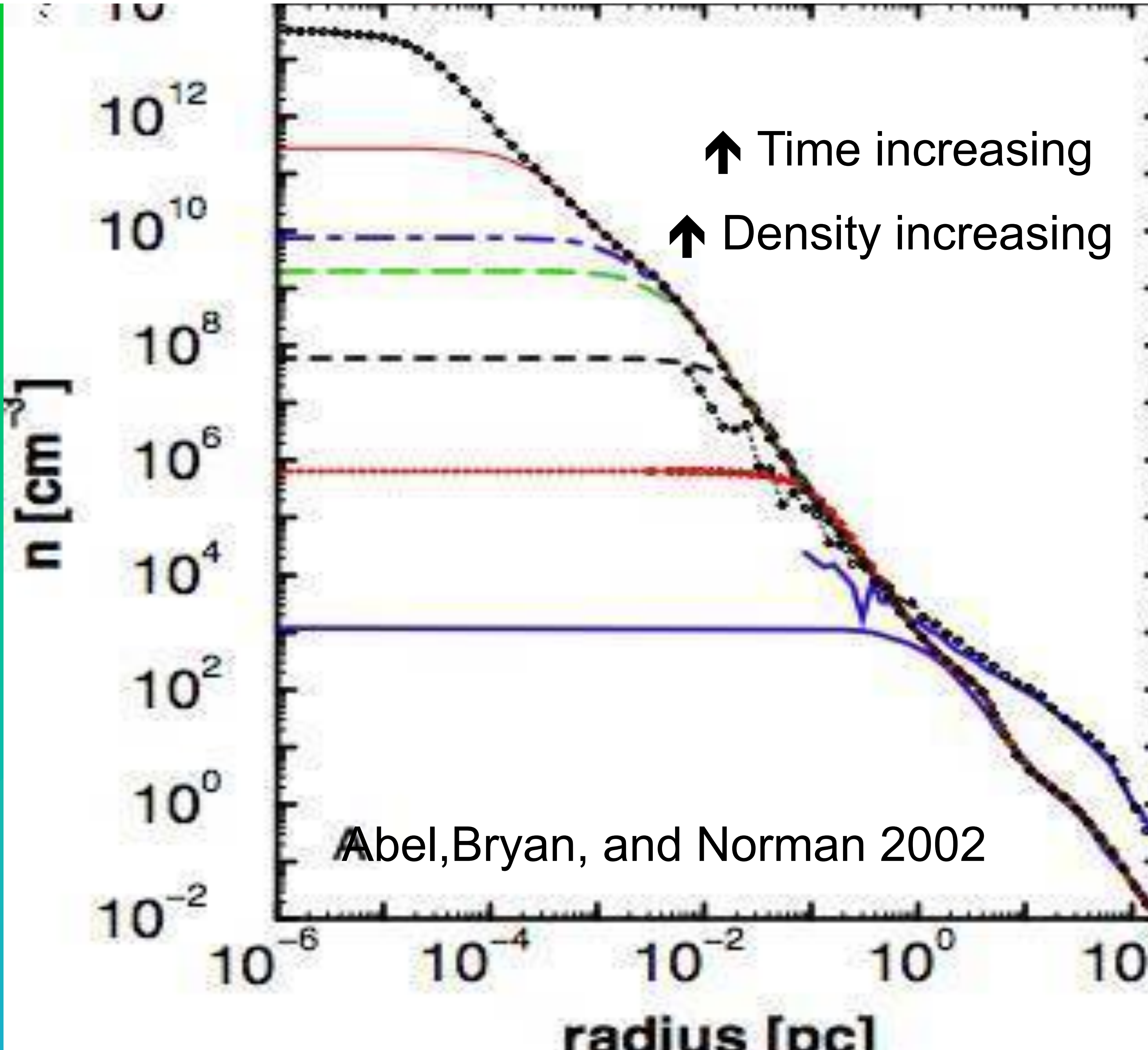
1/3 electrons

1/3 photons

1/3 neutrinos

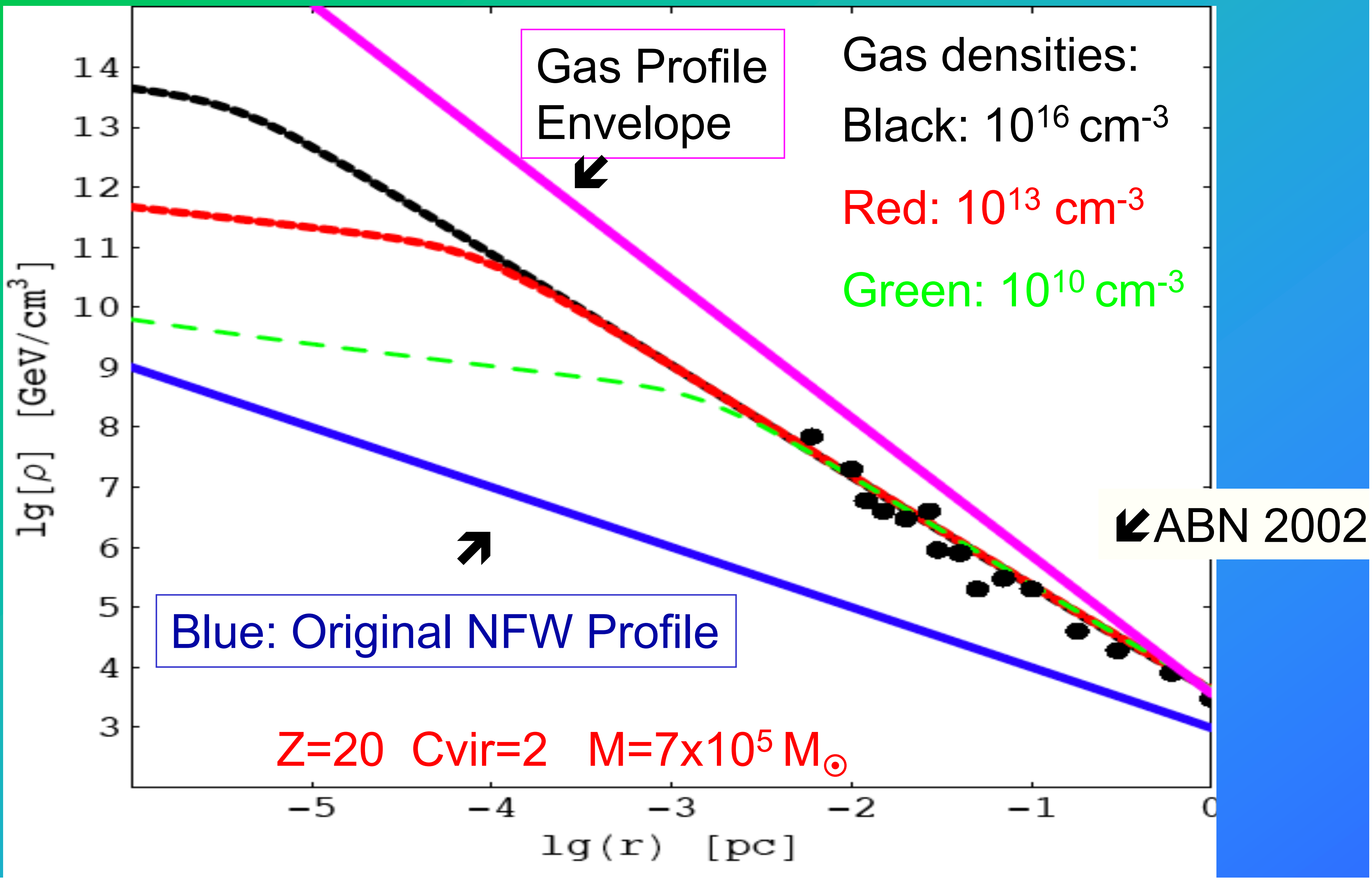
First Condition: Large DM density

- DM annihilation rate scales as DM density squared, and happens wherever DM density is high. The first stars are good candidates: good timing since density scales as $(1+z)^3$ and good location at the center of DM halo
- Start from standard NFW profile in million solar mass DM halo.
- As star forms in the center of the halo, it gravitationally pulls in more DM. Treat via **adiabatic contraction**.
- If the scattering cross section is large, even more gets **captured** (treat this possibility later).



Time increasing
Density increasing
Abel,Bryan, and Norman 2002
n [cm^{-3}]
radius [pc]
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-6}
10^{-4}
10^{-2}
10^{0}

DM profile and Gas



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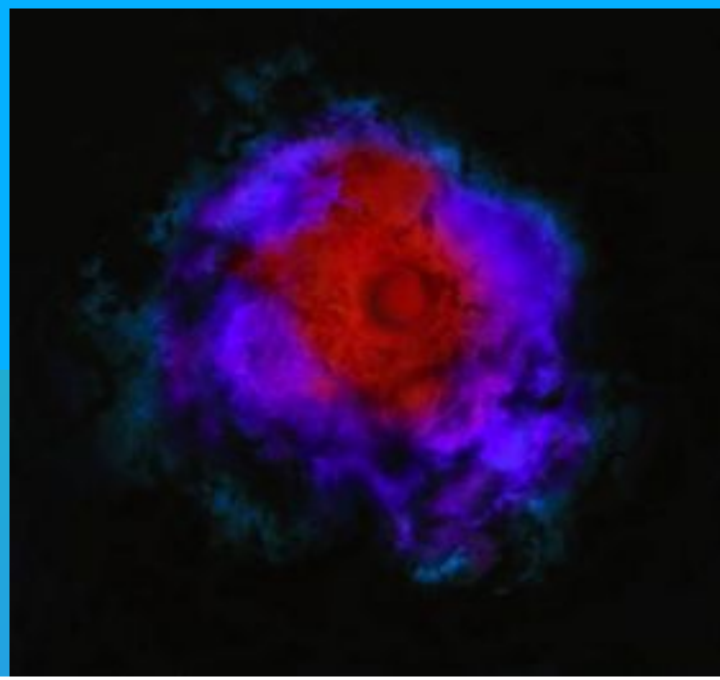
Leads to New Phase



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f_Q :

1/3 electrons

1/3 photons

1/3 neutrinos

Crucial Transition

- At sufficiently high densities, most of the annihilation energy is trapped inside the core and heats it up
- When:

$$m_\chi \approx 1\ \mathrm{GeV} \quad \rightarrow \quad n \approx 10^{9}/\mathrm{cm}^3$$

$$m_\chi \approx 100\ \mathrm{GeV} \quad \rightarrow \quad n \approx 10^{13}/\mathrm{cm}^3$$

$$m_\chi \approx 10\ \mathrm{TeV} \quad \rightarrow \quad n \approx 10^{15-16}/\mathrm{cm}^3$$

- The DM heating dominates over all cooling mechanisms, impeding the further collapse of the core

Three Conditions for Dark Stars (Paper 1)

- 1) OK! Sufficiently High Dark Matter Density
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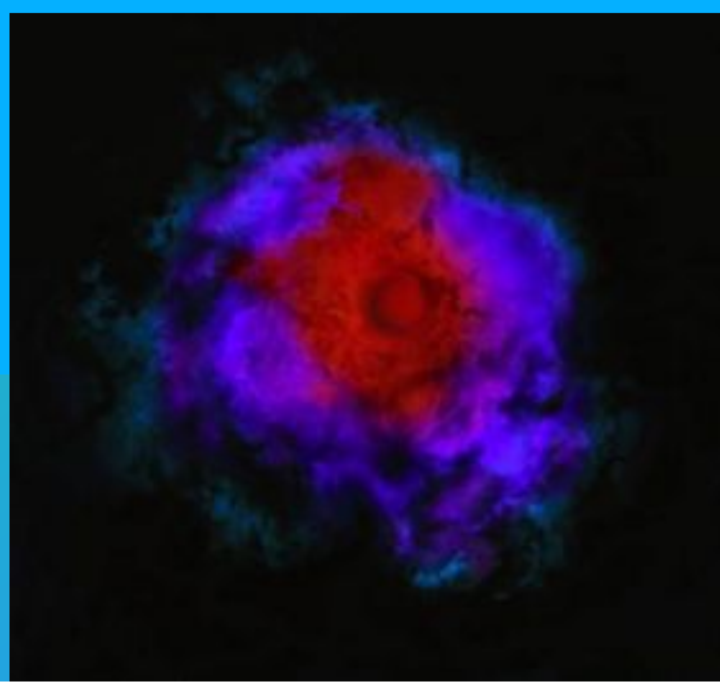
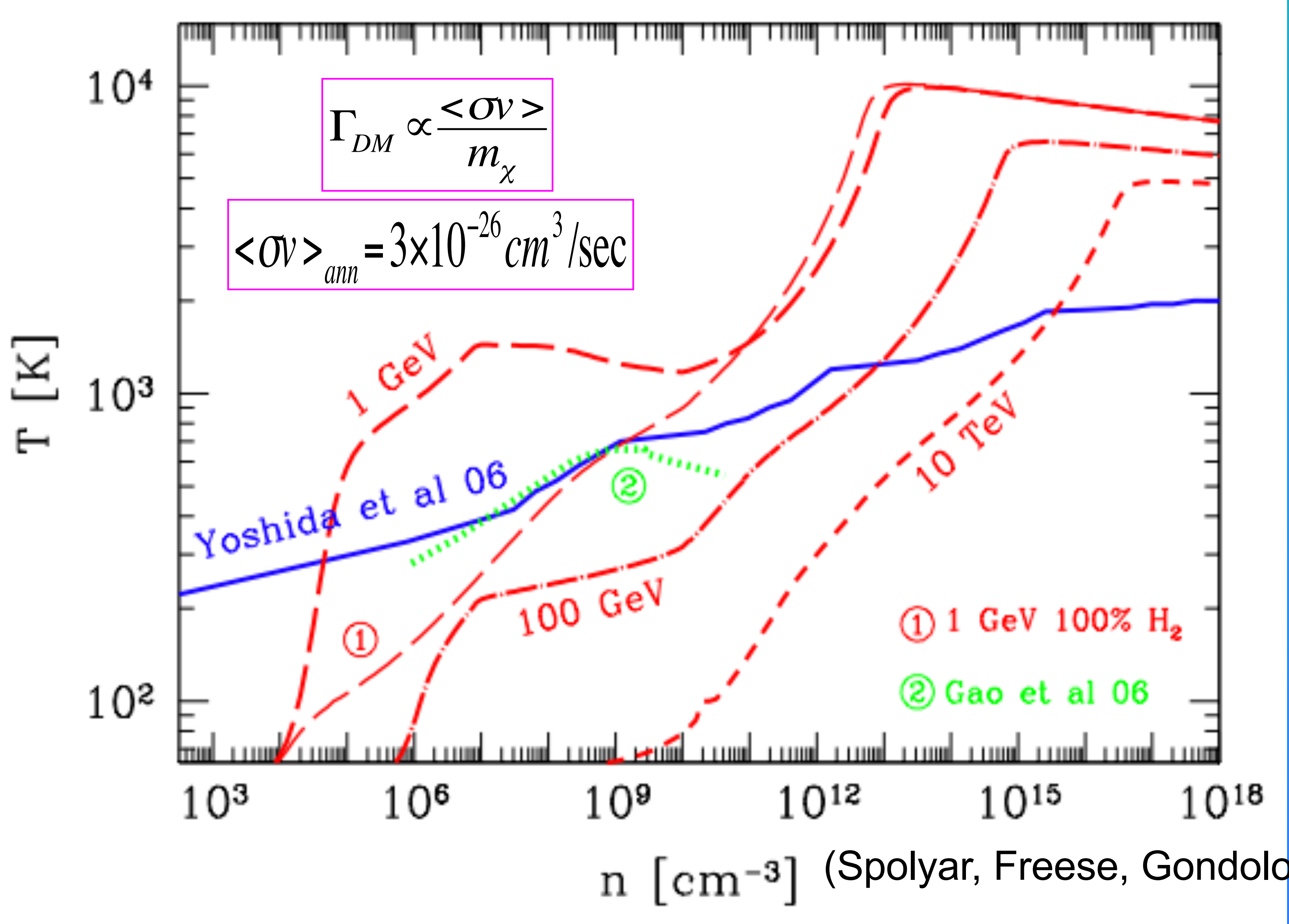
New Phase

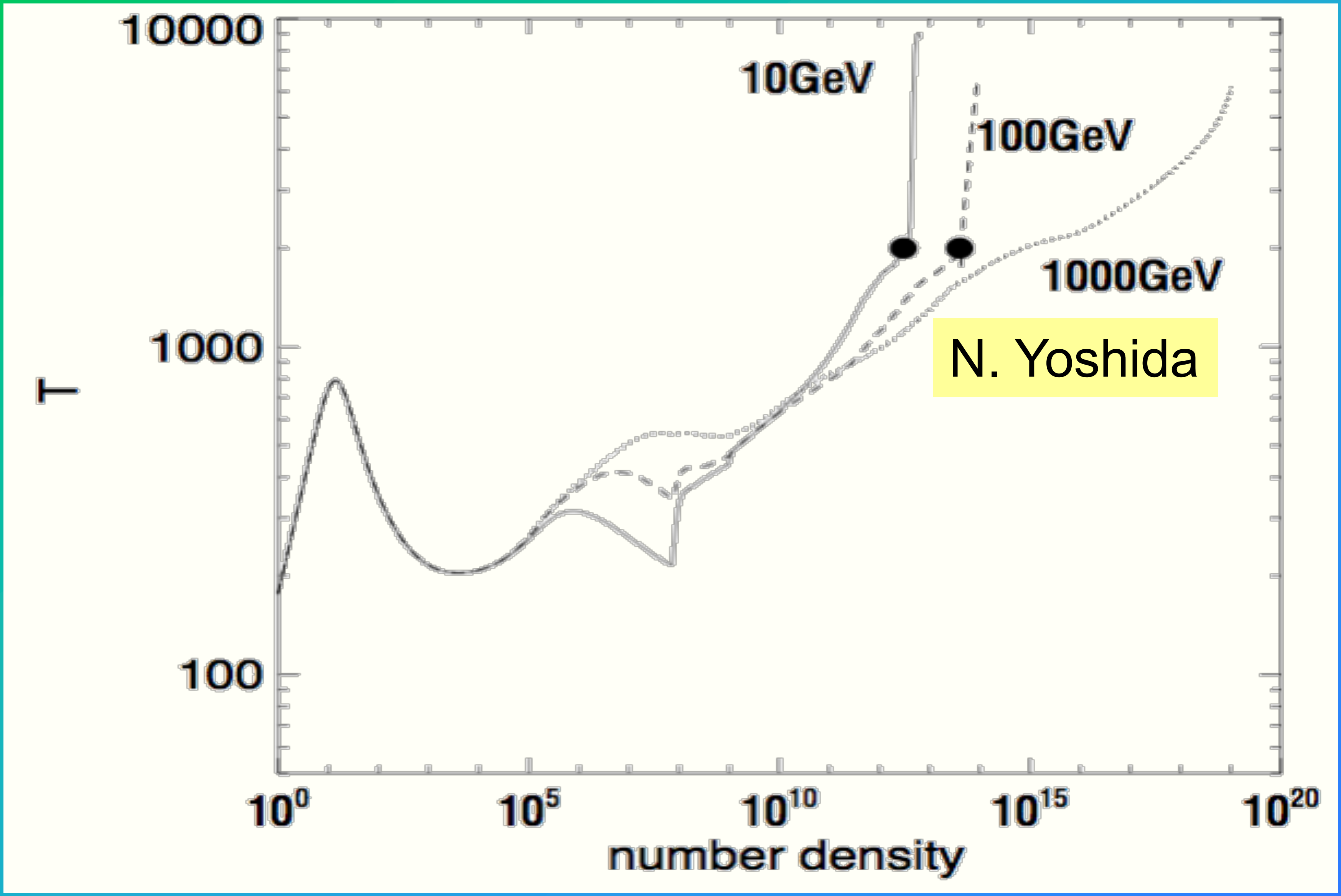


DM Heating dominates over cooling when the red lines cross the blue/green lines (standard evolutionary tracks from simulations). Then heating impedes further collapse.



(Spolyar, Freese, Gondolo April 2007)

New proto-Stellar Phase:
fueled by dark matter



At the moment heating wins:

- "Dark Star" supported by DM annihilation rather than fusion
- They are giant diffuse stars that fill Earth's orbit

$m_\chi \approx 1$ GeV	core radius 960 a.u.	Mass 11 $M_\odot$
$m_\chi \approx 100$ GeV	core radius 17 a.u.	Mass 0.6 $M_\odot$

- THE POWER OF DARKNESS: DM is only 2% of the mass of the star but provides the heat source

DS Evolution (w/ Peter Bodenheimer)

- Find hydrostatic equilibrium solutions
- Look for polytropic solution, $p = K\rho^{1+1/n}$

  for low mass n=3/2 convective,

  for high mass n=3 radiative

  (transition at 100-400 $M_\odot$)
- Start with a few solar masses, guess the radius, see if DM luminosity matches luminosity of star (photosphere at roughly 6000K). If not adjust radius until it does. Smaller radius means larger gas density, pulls in more DM via adiabatic contraction, higher DM density and heating. Equilibrium condition:

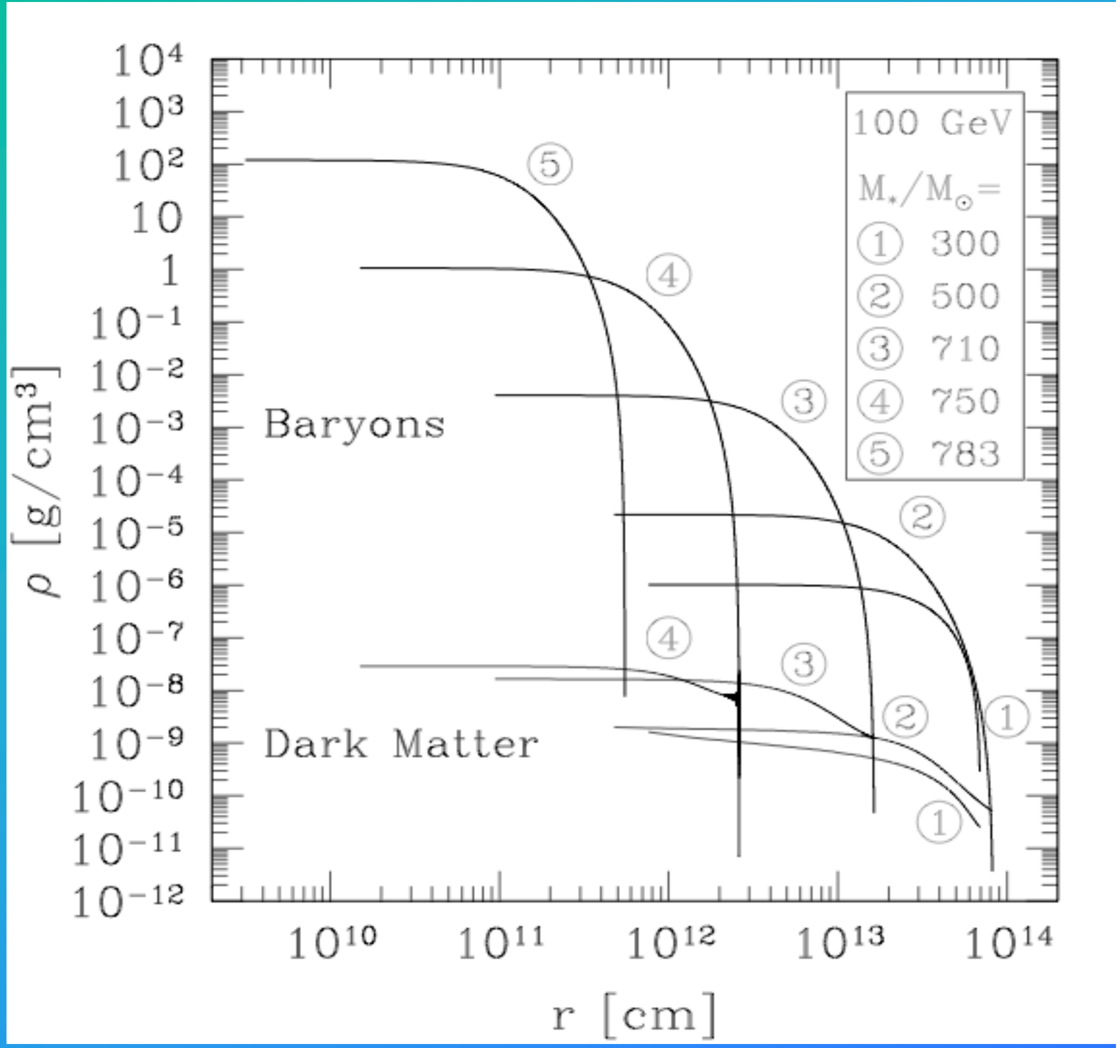
$$L_{DM} = L_*$$

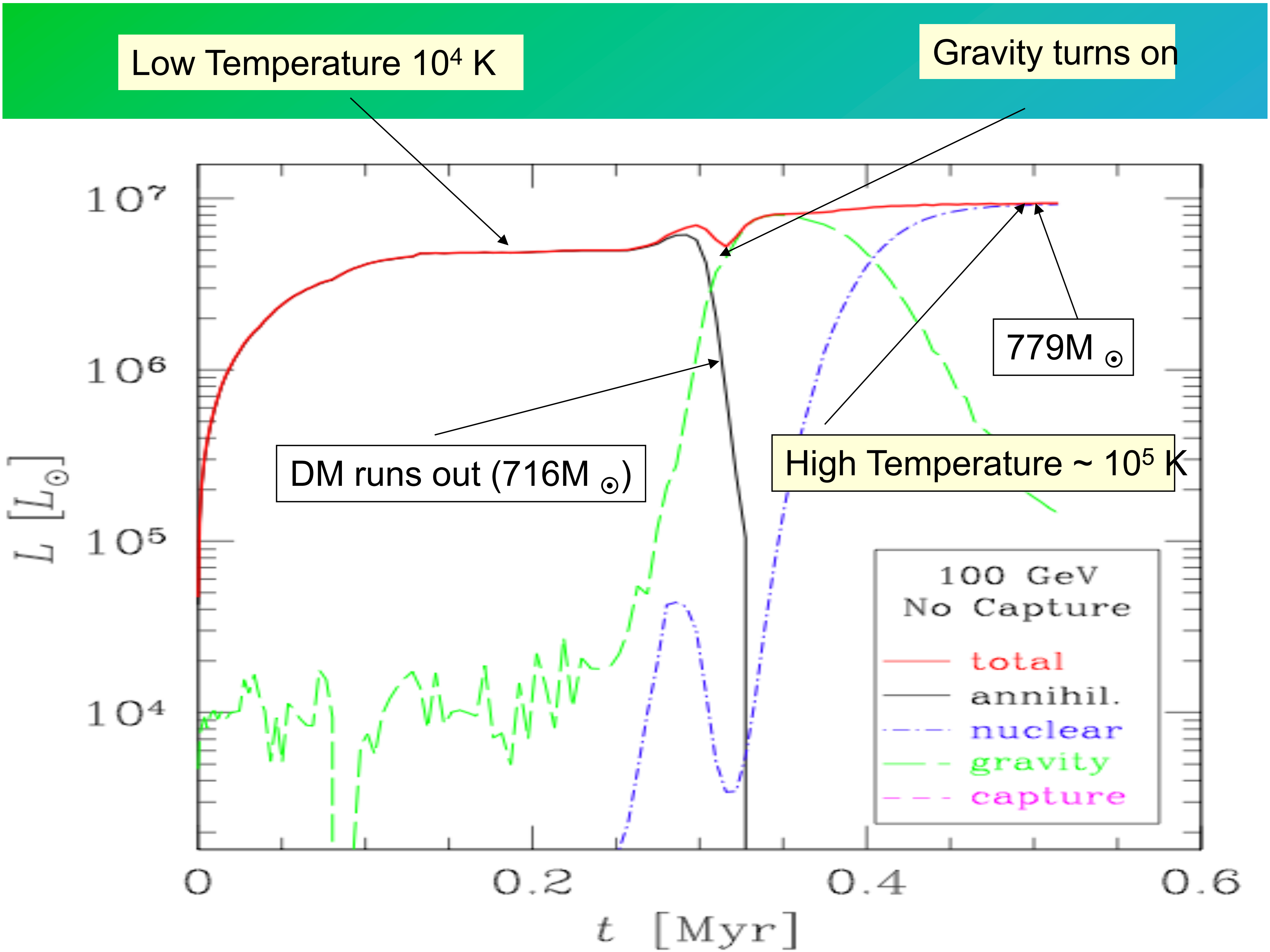
Building up the mass

- Start with a few $M_{\odot}$ Dark Star, find equilibrium solution
- Accrete mass, one $M_{\odot}$ at a time, always finding equilibrium solutions
- N.b. as accrete baryons, pull in more DM, which then annihilates
- Continue until you run out of DM fuel
- VERY LARGE FIRST STARS. Then, star contracts further, temperature increases, fusion will turn on, eventually make giant black hole

Following DS Evolution

- Gas Accretes onto molecular hydrogen Core, the system eventually forms a star.
- We then solve for stellar Structure by:
  - Self consistently solve for the DM density and Stellar structure
  - (Overly Conservative) DM in spherical halo. We later relax this condition




Low Temperature 10^4 K
Gravity turns on
DM runs out (716M $_\odot$)
779M $_\odot$
High Temperature ~ 10^5 K
10^7
10^6
10^5
10^4
$L\ [L_\odot]$
0
0.2
0.4
0.6
t [Myr]
100 GeV
No Capture
total
annihil.
nuclear
gravity
capture

HERTZSPRUNG-RUSSELL DIAGRAM FOR DARK STARS

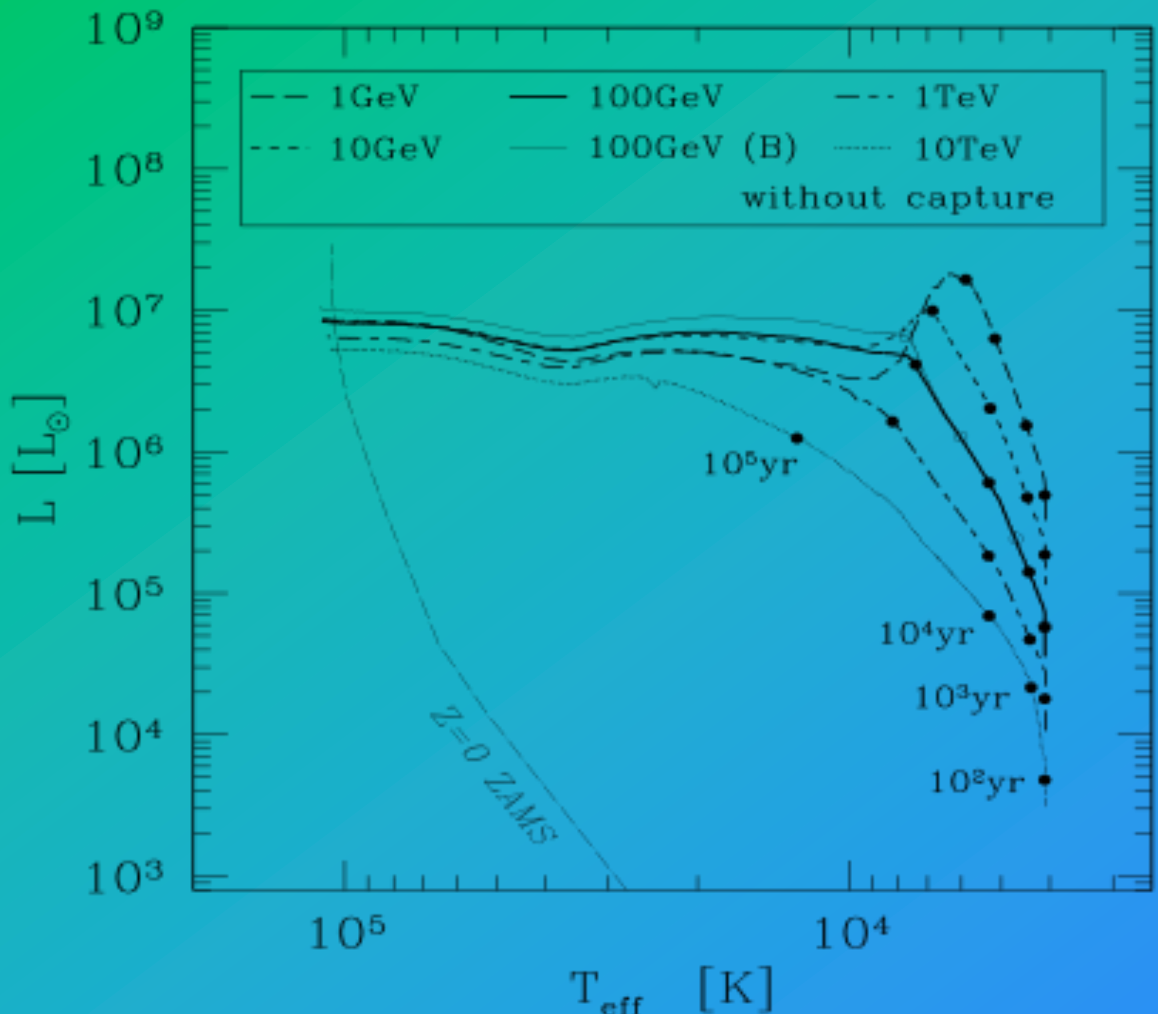


FIG. 1.— Evolution in the H-R diagram, for 5 different particle masses as indicated in the legend. The luminosity is given in solar units and the temperature is in Kelvin. The dots indicate a series of time points, which are the same for all cases. The open dots distinguish the 100 GeV (B) case from the 100 GeV case. All cases are calculated with the accretion rate given by Tan & McKee (2004) except the curve labelled 100 GeV (B), which is calculated with the rate given by O'Shea & Norman (2007). The metal-free zero-age main sequence ($Z = 0$ ZAMS) is taken from Schaerer (2002). The peak below 10^4K in the 1 GeV case is due to the overwhelming DM luminosity in this case.

DS Basic Picture

- We find that DS are:
  - Massive: can grow to ten million $M_{\odot}$
  - Large-a few a.u. (size of Earth's orbit around Sun)
  - Luminous: more than 10^7 solar
  - Cool: 10,000 K vs. 100,000 K plus
    - Will not reionize the universe.
  - Long lived: more than 10^6 years, even till today?.
  - With Capture or nonCircular orbits, get even more massive, brighter, and longer lived

How big do Dark Stars get?

- KEY POINT: **As long as the star is Dark Matter powered, it can keep growing** because its surface is cool: surface temp 10,000K (makes no ionizing photons)
- Therefore, baryons can keep falling onto it without feedback.
- Previously, we considered spherical haloes and thought the dark matter runs out in the core, making a small hole in the middle with no dark matter. We made 1000 solar mass DS.
- Wrong: Haloes are triaxial! MUCH MORE DM is available and the DS can end up Supermassive up to ten million solar masses.
- Second mechanism to bring in more dark matter: capture

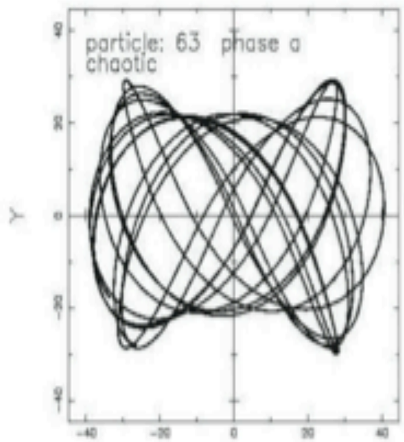
Is there enough DM?

Spherical Halos

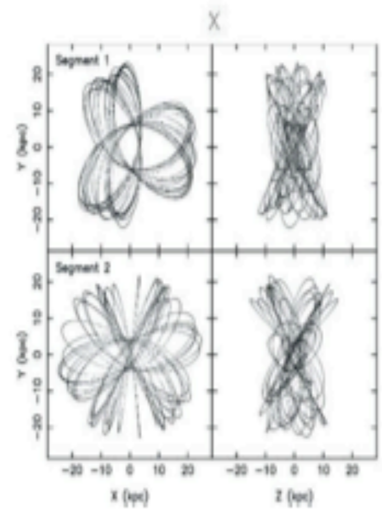
- DM orbits are planar rosettes (Binney & Tremaine '08).
- The Dark Star creates a loss cone that cannot be refilled.

Halos are actually Prolate-Triaxial (Bardeen et al. '86).

- Two classes of centrophilic orbits. Box and Chaotic orbits (Schwarzchild '79).
- Traversing arbitrarily close to the center and refilling the loss cone.
- The loss cone could remain full for 10^4 times longer than in the case of a Spherical Halo (Merritt & Poon '04).



Box Orbit



Chaotic Orbit

A particle that comes through the center of the DS can be annihilated. However, that particle was not on an orbit that would pass through the center again anyway. The next particle will come in from a different orbit.

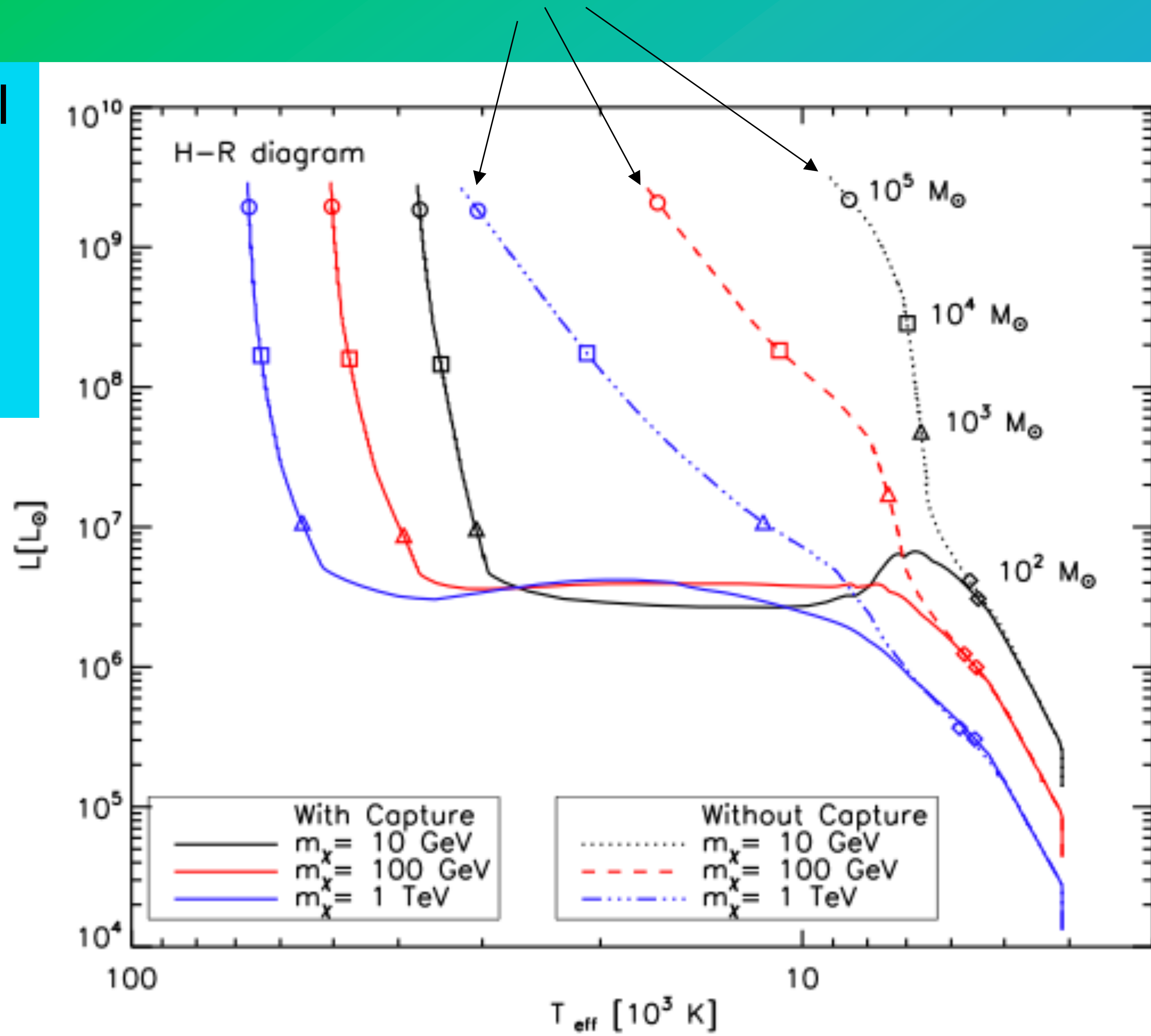
SUPERMASSIVE dark stars (SMDS) from extended adiabatic contraction

- Previously we thought dark matter runs out in a million years with 800 $M_\odot$ stars: end up with a donut, i.e., big spherical halo of dark matter with hole in the middle
- But, triaxial haloes have all kinds of orbits (box orbits, chaotic orbits) so that much more dark matter is in there. Dark stars can grow much bigger and make supermassive stars, 10^5-10^7 $M_\odot$, last much longer, and reach 10^9-10^{11} $L_\odot$. Some may live to today
- Visible in James Webb Space Telescope.
- Leads to (as yet unexplained) big black Holes.

Additional mechanism: see Umeda etal (JCAP 2009)

Super Massive DS due to extended adiabatic contraction since reservoir has been replenished due to orbital structure

Assuming all of the baryons can accrete in a 10^6 M $_{\odot}$ halo



Additional possible source of DM fuel: capture

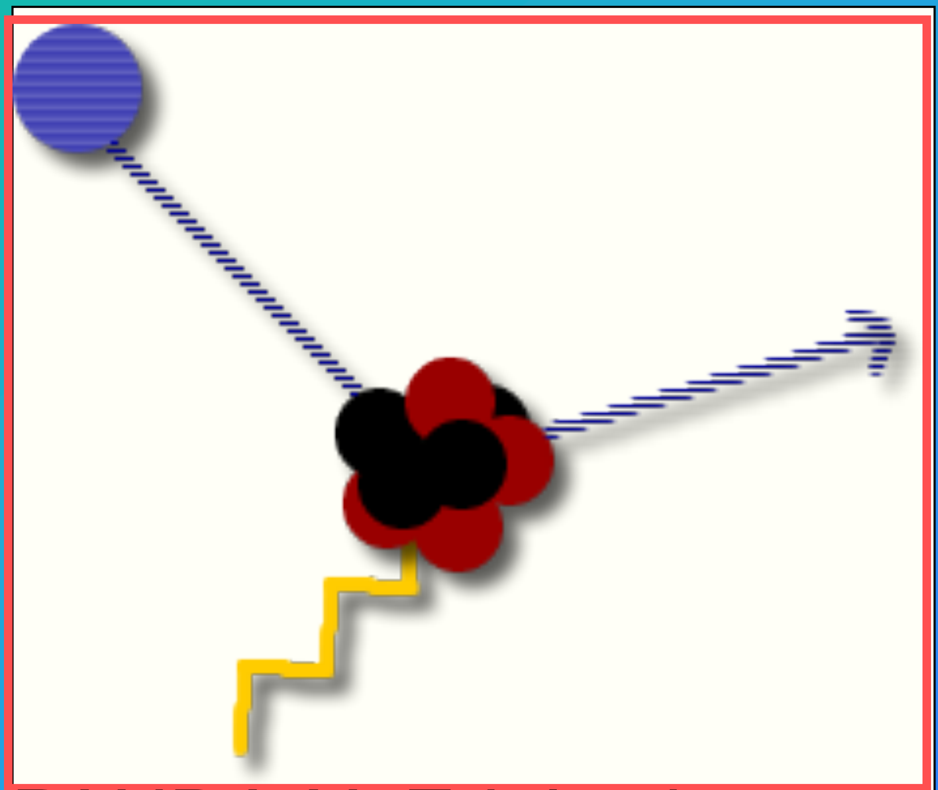
- Some DM particles bound to the halo pass through the star, scatter off of nuclei in the star, and are captured. (This it the origin of the indirect detection effect in the Earth and Sun).
- Two uncertainties:

  (I) ambient DM density (ii) scattering cross section must be high enough.
- Whereas the annihilation cross section is fixed by the relic density, the scattering cross section is a free parameter, set only by bounds from direct detection experiments.

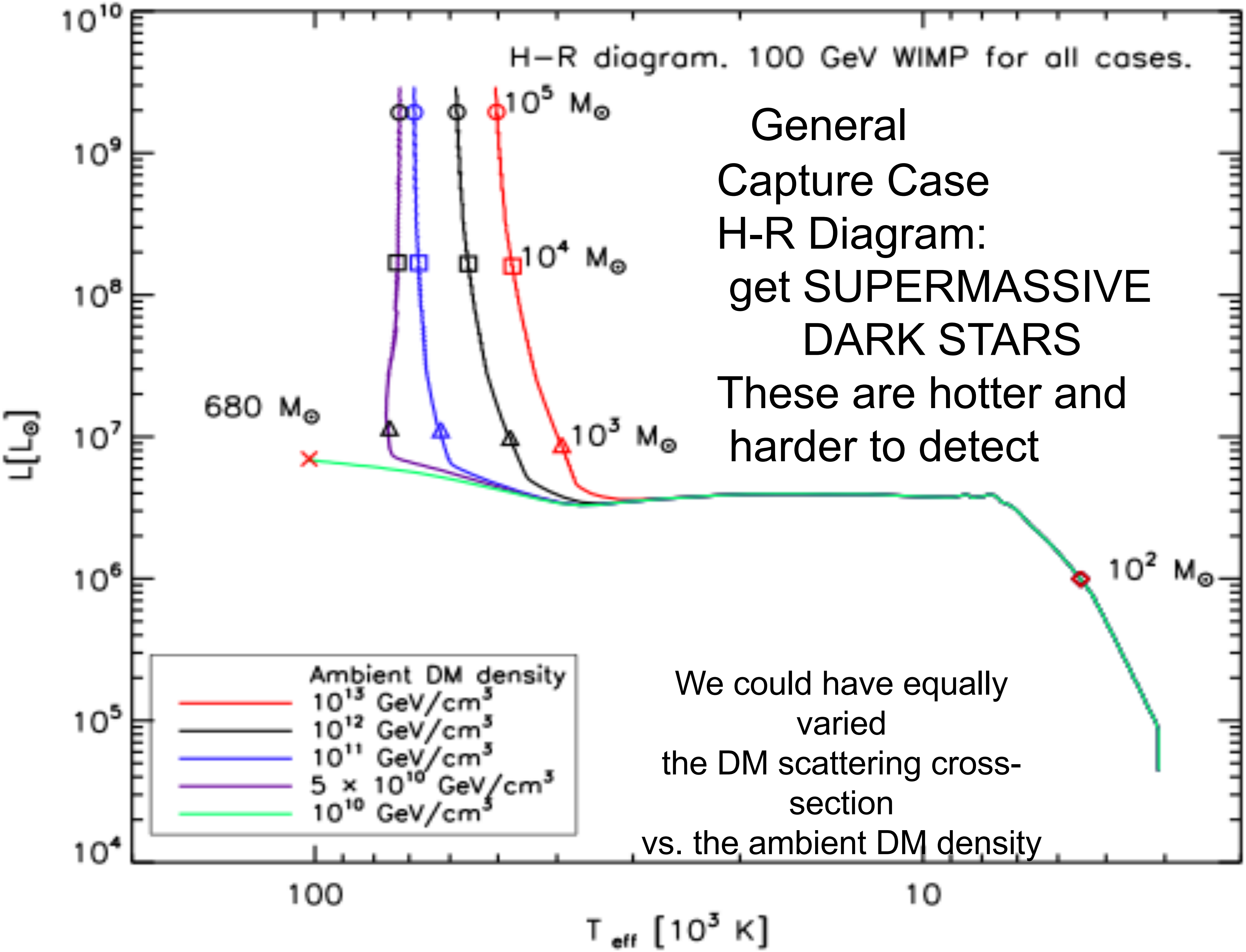
Freese, Aguirre, Spolyar 08; Iocco 08

WIMP scattering off nuclei leads to capture of more DM fuel

Some DM particles bound to the halo pass through the star, scatter off of nuclei in the star, and are captured.



This is the same scattering that CDMS, XENON, LUX, PANDA-X, Edelweiss, DAMA, CRESST, etc are looking for (Direct Detection)



General
Capture Case
H-R Diagram:
get SUPERMASSIVE
DARK STARS
These are hotter and
harder to detect

We could have equally
varied
the DM scattering cross-
section
vs. the ambient DM density

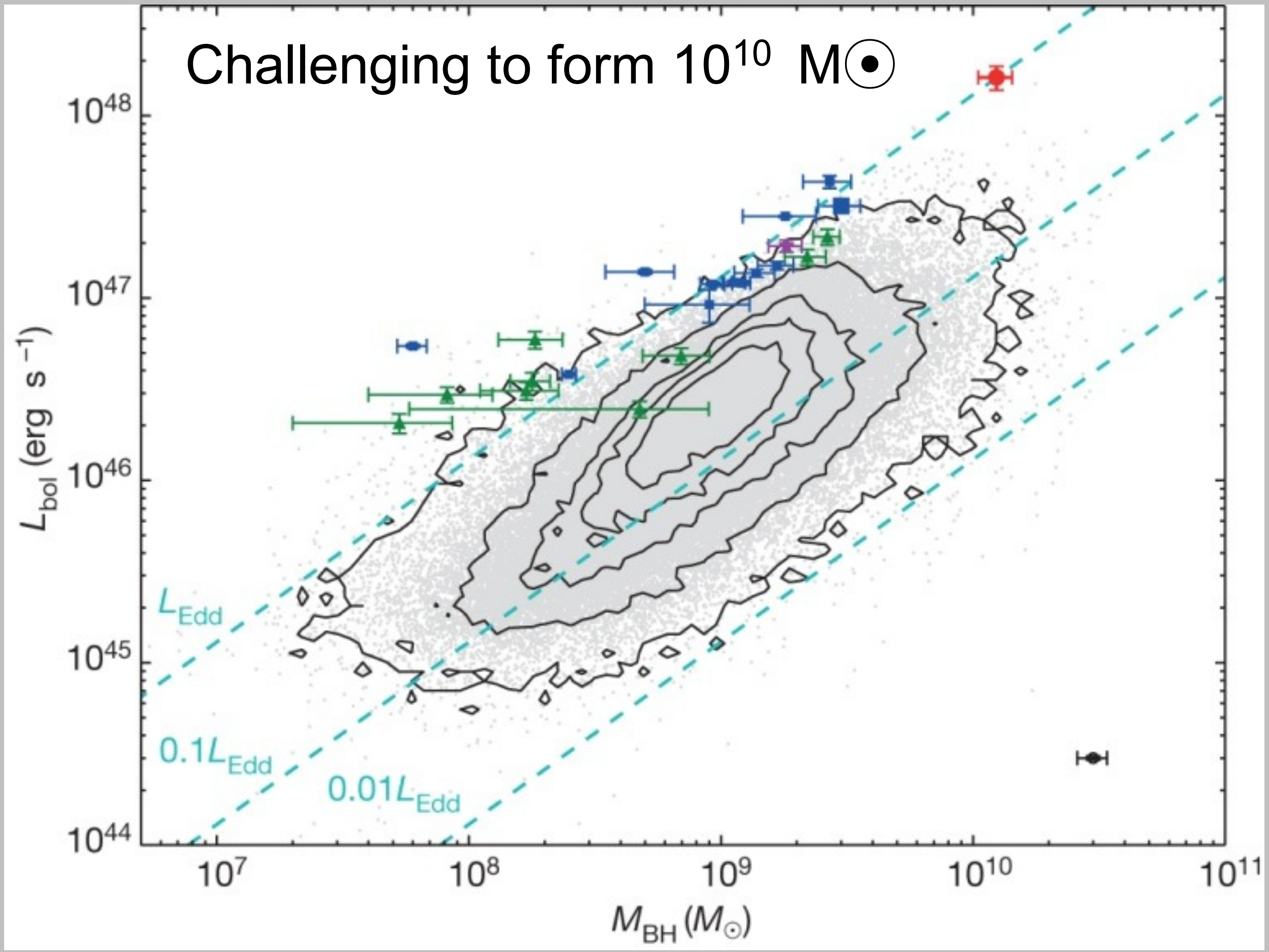
Lifetime of Dark Star

- The DS lives as long as DM orbits continue through the DS or it captures more Dark Matter fuel: millions to billions of years.
- The refueling can only persist as long as the DS resides in a DM rich environment, I.e. near the center of the DM halo. But the halo merges with other objects.
- You never know! They might exist today.
- Once the DM runs out, switches to fusion.

What happens next?
BIG BLACK HOLES

- Star reaches $T=10^7K$, fusion sets in.
- A. Heger finds that fusion powered stars heavier than 153,000 solar masses are unstable and collapse to BH
- Less massive Pop III star lives a million years, then becomes a Black Hole
- Helps explain observed black holes:
- (i) in centers of galaxies
- (ii) billion solar mass BH at z=6 (Fan, Jiang)
- (iii) intermediate mass BH
- .

SupperMassive Black holes from Dark Stars
Very Massive progenitor Million Solar Masses
No other way to form supermassive BH this early z=6

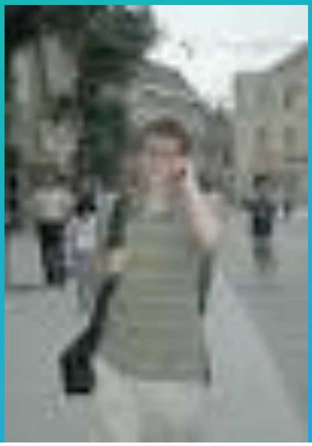


X-B Wu *et al. Nature* **518**, 512-515 (2015) doi:10.1038/nature14241

nature

Observing Dark Stars

- Supermassive Dark Stars may be detected in upcoming James Webb Space Telescope
- One of JWST goals is to find first stars: only if they are dark stars is this goal realizable



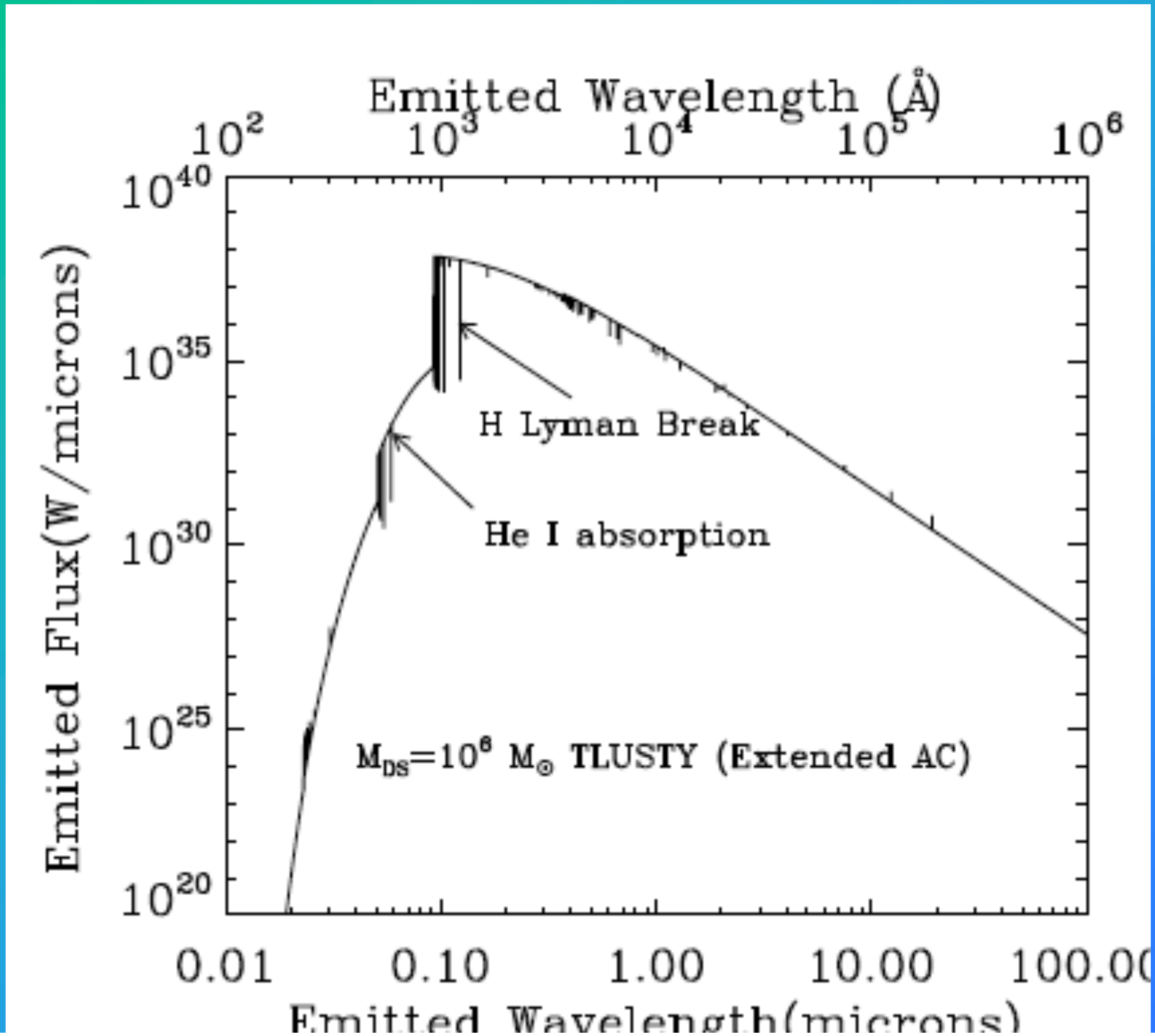
Cosmin Ilie, Paul Shapiro

Pat Scott

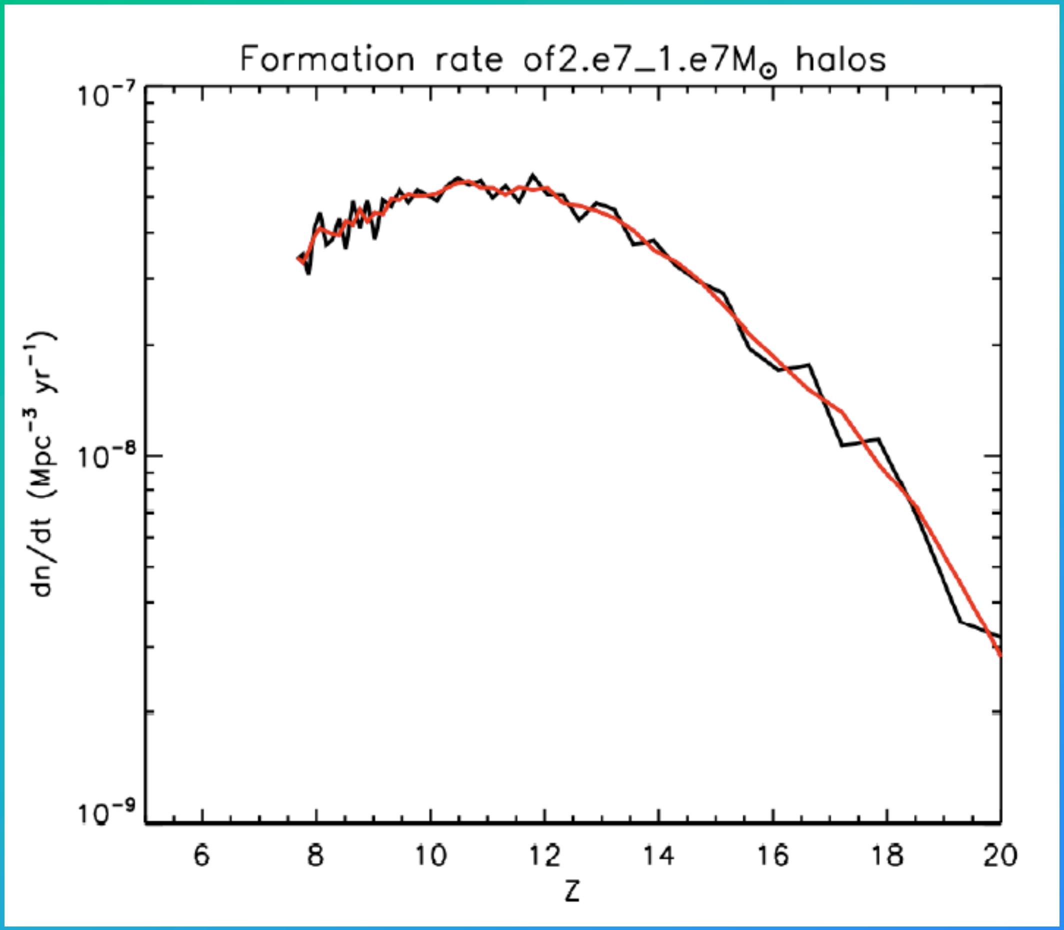
DS Spectrum from TLUSTY (stellar atmospheres code)

Pat Scott

n.b. DS are made of hydrogen and helium only

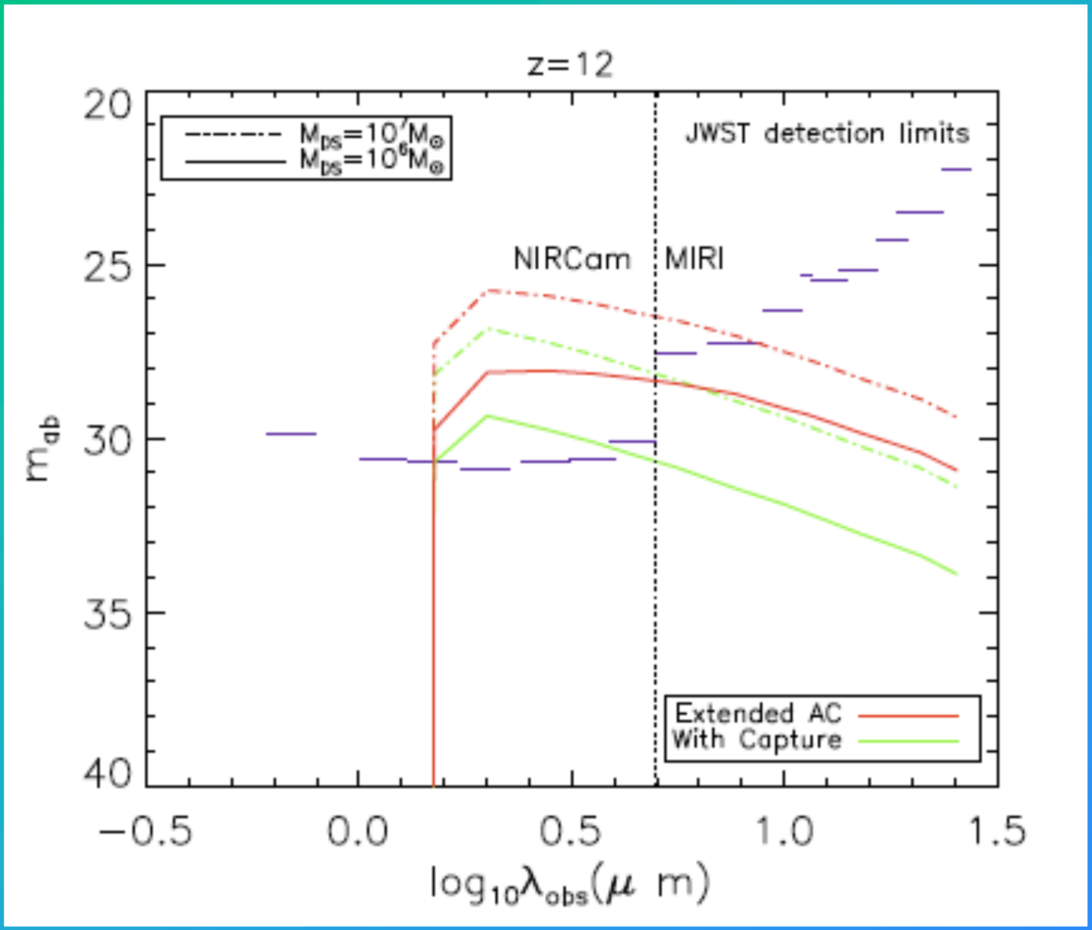


Minihalo formation rate

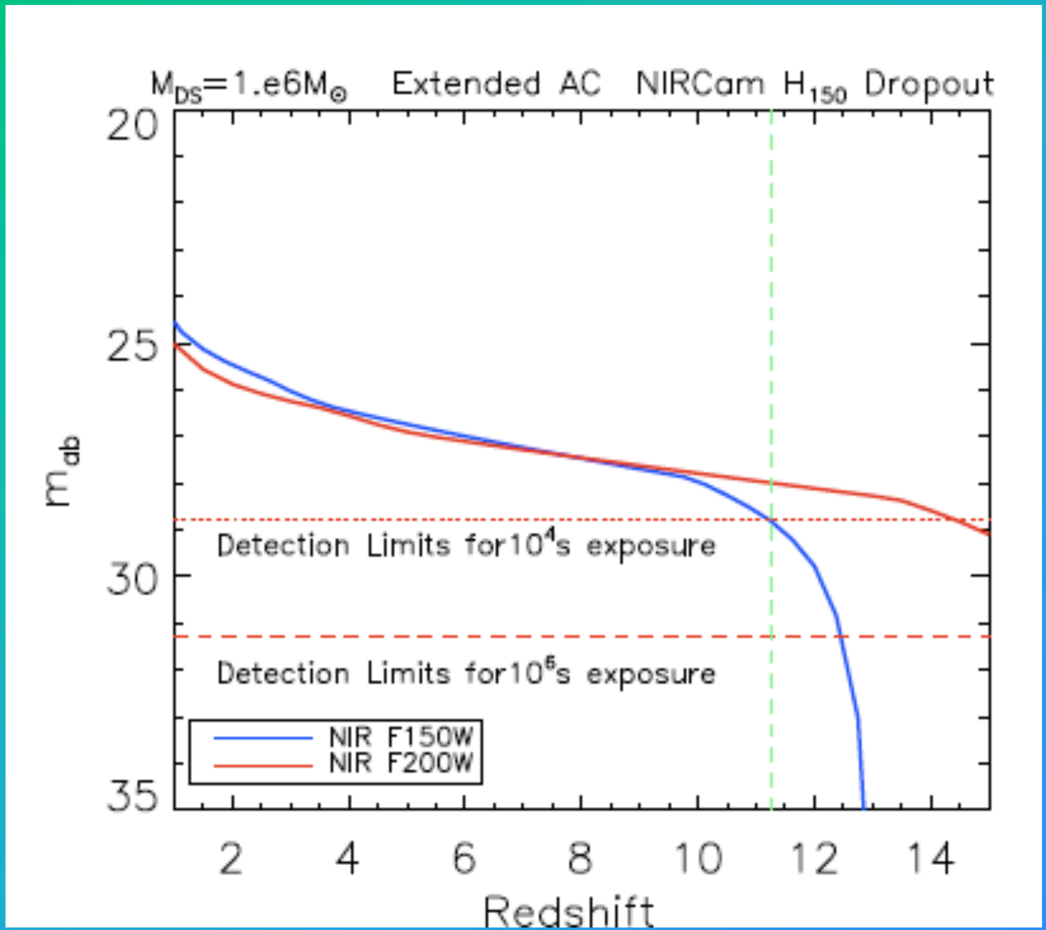


Shapiro,
Iliev

Dark Stars in JWST, sequel to HST



Million solar mass SMDS as H-band dropout



(see in 2.0 micron but not 1.5 micron filter, implying it's a z=12 object)

Numbers of SMDS detectable with JWST as H-band dropouts

(see in 2.0 micron but not 1.5 micron filter, implying it's z=12 object)

Upper limits on numbers of SMDS detectable with JWST as H_{150} dropout

$M_{DS}(M_\odot)$	Formation Scenario	Bounds from HST	N_{obs}^{FOV}	N_{obs}^{multi}
10^6	Extended AC	Maximal Bounds	$\lesssim 1$	10
10^6	With Capture	Maximal Bounds	2	32
10^7	Any	Maximal Bounds	$\lesssim 1$	~ 1
10^6	Extended AC	Intermediate	45	709
10^6	With Capture	Intermediate	137	2128
10^7	Any	Intermediate	4	64
10^6	Extended AC	Number of DM halos	28700	444750
10^6	With Capture	Number of DM halos	28700	444750
10^7	Any	Number of DM halos	155	2400

Table 3. Upper limits on the number of SMDS detections as H_{150} dropouts with JWST. In first three rows (labeled "Maximal Bounds") we assume that all the DS live to below z=10 where they would be observable by HST, and we apply the bounds on the numbers of DS $f_{\rm SMDS}$ from HST data in Section 4.2. The middle three rows (labeled "Intermediate") relax those bounds by assuming that only $\sim 10^{-2}$ of the possible DS forming in z=12 haloes make it through the HST observability window. For comparison we also tabulate in the last three rows the total number of potential DM host halos in each case. We also split the number of observations in two categories, N_{obs}^{FOV} and N_{obs}^{multi}. The first assumes a sliver with the area equal to the FOV of the instrument (9.68 arcmin^2), whereas in the second we assume multiple surveys with a total area of 150 arcmin^2 . Note that for the case of the $10^7 M_\odot$ SMDS the predictions are insensitive to the formation mechanism.

Dark stars Pulsations

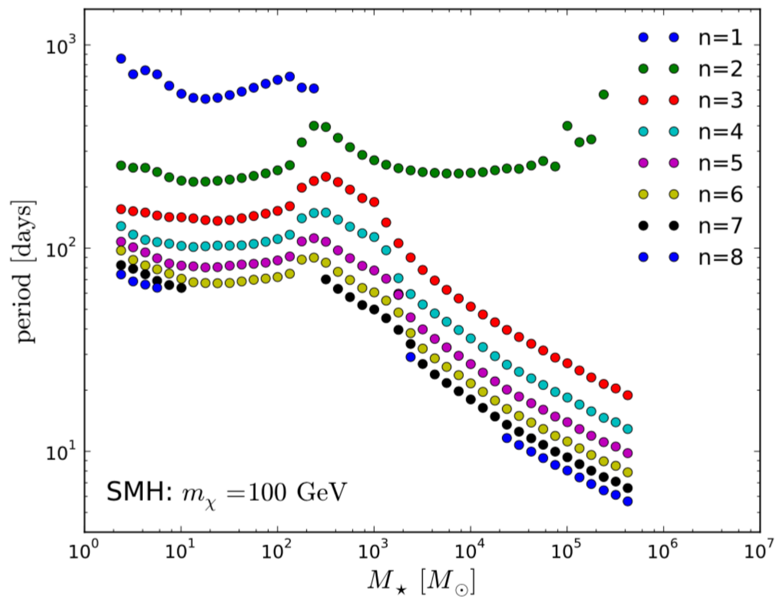


Figure 9. Radial, adiabatic pulsation periods as a function of DS mass for a WIMP mass of 100 GeV and a DS forming in SMH. The periods are given in the restframe of the DS. The curves are for different overtone number, from the fundamental radial oscillation $n = 1$ (upper-most curve) to $n = 8$ (lower-most curve); see also Ref.[16].

Finding pulsations allows differentiation in data from early galaxies
Also, someday will provide standard candles

Final Thoughts: *IMF*

- The IMF of the first fusion powered stars may be determined by the Dark Matter encountered by their Dark Star progenitors: as long as there is DM, the DS keeps growing
- Depends on cosmological merger details of early haloes, million to hundred million solar mass haloes

Dark Stars (conclusion)

- The dark matter can play a crucial role in the first stars
- The first stars in the Universe may be powered by DM heating rather than fusion
- These stars may be very massive (up to 10 million solar masses) and bright (up to ten billion solar luminosities), can be precursors to Supermassive Black Holes, and can be detected by JWST
- WIMPs could first be detected by discovering dark stars